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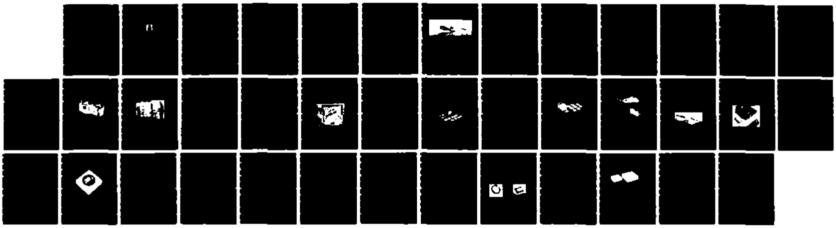

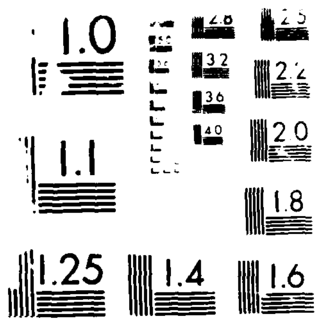
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# FOREIGN TECHNOLOGY DIVISION

AIR FORCE SYSTEMS COMMAND

CONMILIT

(Selected Articles)

FOREIGN TECHNOLOGY DIVISION

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FTD-ID(RS)T-1168-86

# HUMAN TRANSLATION


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TABLE OF CONTENTS:

# INERTIA NAVIGATIONAL SYSTEMS OF MILITARY AIRCRAFT AND THEIR COMBAT APPLICATIONS

-----Providing Accurate Navigational and Attack Parameters

Xu Guozhen

An inertia navigational system is the central information source which independently and continuously provides aircraft with various flight parameters and is a type of ideal navigational equipment. Moreover, the inertia platform as a speed sensor on aircraft has become the standard of precision weapon aiming and delivery, and it is the heart of the aircraft weapon aiming system.

## Inertia Navigational Equipment on Military Aircraft

Among the various aircraft navigational equipment, inertia navigational equipment is currently the most used and technologically mature type of navigational means. Generally speaking, four parameters are required for navigation, namely, the position, speed, pose and flight direction. Ordinary devices among on-board equipment which are capable of providing this information are:

Vertical gyroscope---to provide pose information.

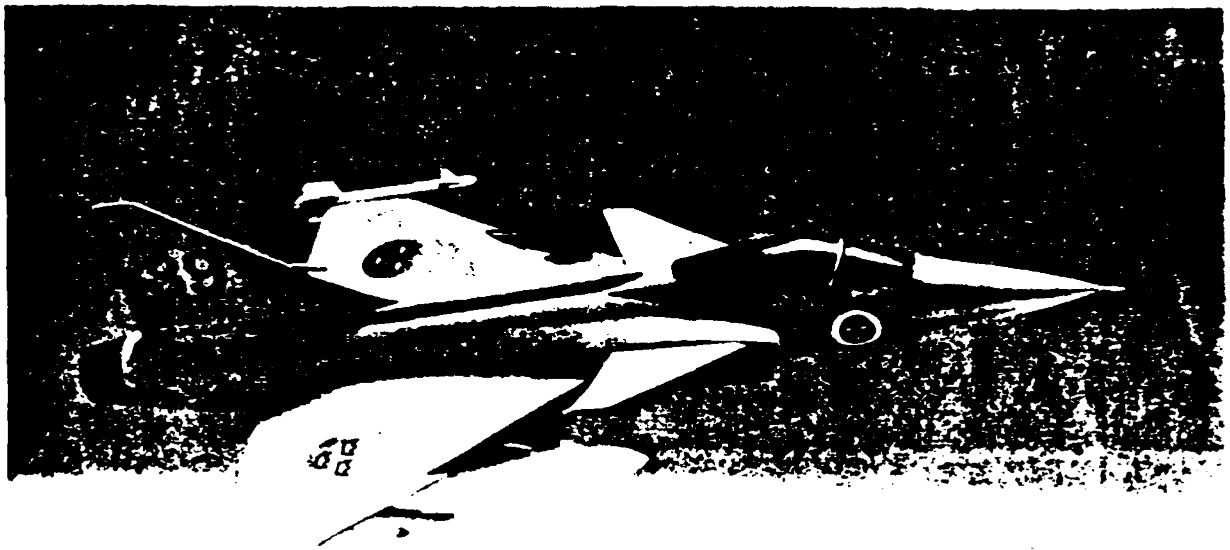
Magnetic compass and gyroscope semi-compass---to provide flight direction information.

Doppler radar and atmospheric data system---to provide speed information.

Navigational radar---to provide position information.

Flight direction pose standard system---to provide pose and flight direction information.

Inertia navigational system---to provide pose, flight direction, speed and position.



Following the F-20 "Tigershark", the Swedish JAS 39 multi-purpose fighter which is under development has adopted Honeywell H423 laser gyroinertia navigational system. The U.S. plans to replace navigational equipment on fighters such as F-15, F-111, etc., and may adopt the derived model of H423.

It is thus clear that among the aforementioned devices only the inertia navigational system can simultaneously provide all four parameters required for navigation; therefore, it is called the central information source on aircraft.

The so-called inertia navigation is based on Newton's principle of inertia and uses inertia component(accelerometer and gyroscope) to measure the acceleration of a moving object and through integral operation to obtain the information required for setting position on an entirely independent basis. In navigational position setting, the

trajectory of a moving object can be obtained through measuring position, speed or acceleration, but acceleration is the only physical quantity which can be measured from inside a moving object. It is apparent that this type of independency feature brings it superiority in military applications and it is briefly described below.

Concealability and All-Weather, Global Navigational Capacity

Inertia navigation is determined by its operational principle, making it unaffected by conditions such as terrain, magnetic field, electromagnetic wave, ocean and land, day and night, aircraft expedient movement, etc. Whether in the ocean, desert, polar regions and areas with a distorted geomagnetic field, it can all function normally; this is also to say that it has the all-weather and global navigational capability. Furthermore, the inertia navigational system not only does not need any ground assistance navigational equipment, but also does not send out any electromagnetic waves; therefore, it has an extremely great concealability and it is especially valuable in the military sector.

Technological Guarantee Capability of Destroying Targets with One Pass

All ground attack experiences have shown that, when surprise attack becomes the primary attack means, minimum loss is maintained through maximum attack capability; this is also to say that attack aircraft must be able to accurately hit the target upon the first pass, for attacking a defense unit with warning system on the second or third pass will definitely inflict extremely high cost in terms of aircraft losses.

Aircraft bomb dropping test statistics conducted in foreign countries have shown that, under the premise of using the same kind of weapon to attack the same target, the accuracy of bomb dropping is 6 milliradians for aircraft adopting inertia navigation/attack system; the accuracy of bomb dropping is 10 milliradians for aircraft adopting the Doppler navigation/attack system; the accuracy of bomb dropping is 15 or 20 milliradians for aircraft adopting atmospheric data navigation/attack

system. This is to say that, in order to obtain the same attack effects, what is needed for sending out one sortie of a single aircraft with an inertia navigation/attack system will require two sorties of aircraft with a Doppler navigation/attack system and four or five sorties will be required for aircraft with an atmospheric data navigation/attack system. In other words, squadrons equipped with inertia navigational equipment possess twice as much attack power as squadrons equipped with a Doppler system and four to five times as much attack power as squadrons equipped with an atmospheric data system (Fig. 1).

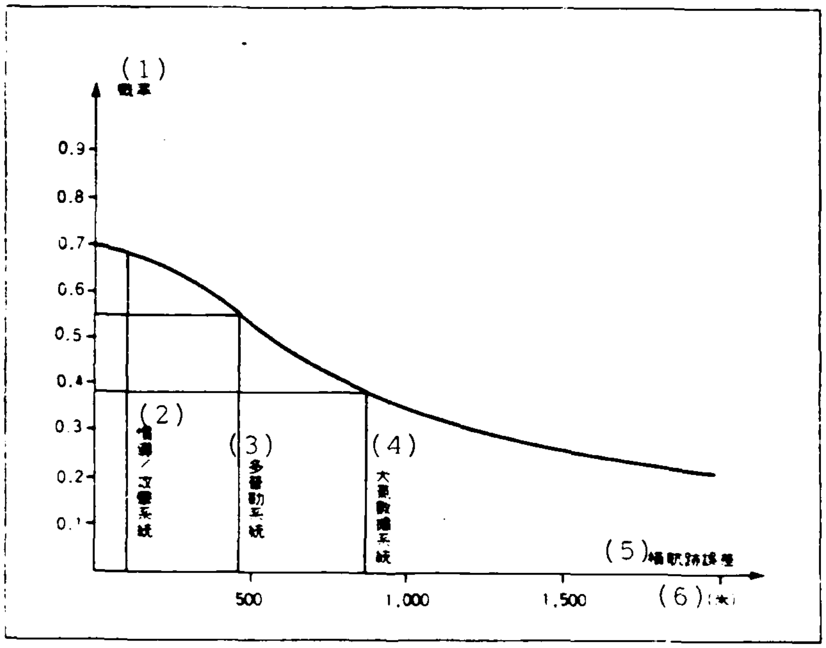



Fig. 1 Comparison between the efficiencies of three kinds of navigation/attack systems.
Key: (1) Probability; (2) Inertia navigation/attack system; (3) Doppler system; (4) Atmopheric data system; (5) Lateral flight track error; (6) meter.

The reason the inertia navigational system allows the carrying aircraft to have the capability of destroying targets in one pass is that it can provide a accurate aircraft velocity vector, and accurate ground speed is the key parameter used to calculate target position and bomb impact

point for ballistic type weapons; that is, the delivery error of ballistic type weapons is primarily determined by the accuracy of velocity.

## Upgrade the Mobility and Maneuverability of Aircraft

The delivery accuracy of aircraft weapons is determined by three major factors: aircraft movement data, target position data and attack cross-section of weapon. When adopting conventional sighting equipment, it is required that the aircraft meet a group of set attack conditions, i.e. the pilot is required to fly a "standard" cross-section, and this limits the maneuverability of aircraft in combat and is also vulnerable to the enemy's counterattack.

If the aircraft is equipped with an inertia navigational system, then it can greatly reduce set-position maneuvering during flight and allow the pilot to freely select flight cross-section, thereby making the aircraft possess capability of conducting all-direction attack and also providing the pilot with full tactical freedom. The U.S. Air Force is currently in the process of researching and manufacturing an advanced tactical fighter(ATF) for the nineties. Its mission cross-sectional chart(Figure 2) includes the two aspects of air-ground attack and air-air dogfight and is accompanied by extremely high-mobile movement(overload can reach 5g). Obviously, this sets forth high requirements in maneuverability and mobility for the navigation/attack system of aircraft.

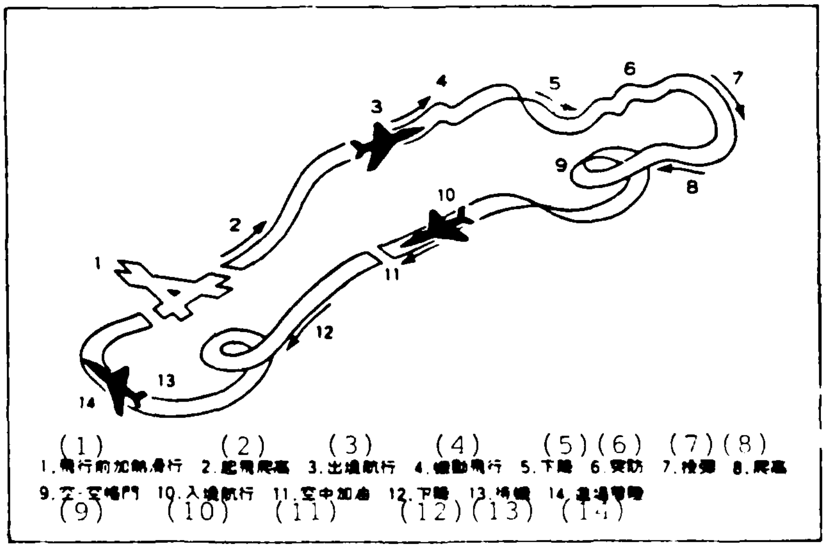


Fig. 2 Flight mission cross-sectional chart of advanced American tactical fighters.
Key: (1) Preflight heated taxiing; (2) Taking off and climbing; (3) Out-bound cruising; (4) Expedient flight; (5) Descending; (6) Penetrating defense; (7) Dropping bombs; (8) Climbing; (9) Air-air dogfight; (10) In-bound cruising; (11) Air refueling; (12) Descending; (13) Holding pattern; (14) Approaching.

## Provide Accurate Parameters for Various Attack Forms of Weapons

There are the following several situations when a fighter conducts ground attack:

---Attack of preset targets

This is the attack of targets with known positions and altitudes which are already stored in computer(Figure 3).

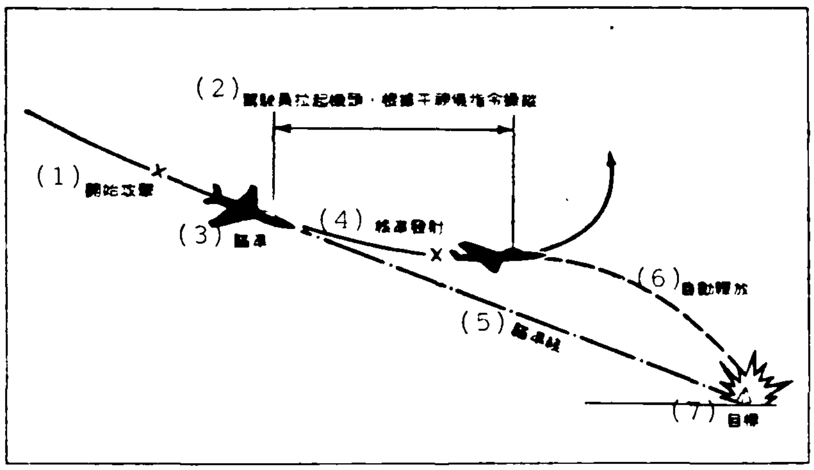



Fig. 3 Attack of preset target by fighter equipped with inertia navigational system.
Key: (1) Commence attack; (2) Pilot pulls up the head and maneuvers according to instructions of horizontal viewing device; (3) Take aim; (4) Approval of firing; (5) Aiming line; (6) Automatic release; (7) Target.

---Attack of random targets

For random targets, it is very possible that there might not be enough time to conduct attack before the target disappears when the

velocity and turning radius of aircraft is rather large. In this case, the position data should be stored in the computer so that it can be spotted in the next pass. Apparently, this kind of capacity is also necessary.

---Attack of offset points

When the target of attack is not visible, its surrounding outstanding features (e.g., road intersections, water towers, bridges, etc.) can be used as markings. Since the distance between the target and the marking is known, the pilot needs only to use this ground signal as an offset aim and the invisible target can be automatically attacked, relying upon the inertia navigation/attack system(Figure 4).

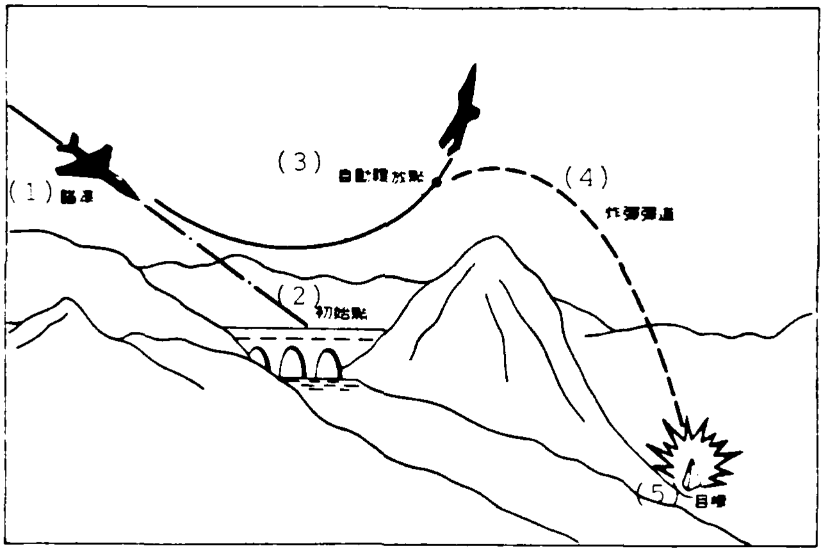



Fig. 4 Fighter equipped with inertia navigational system conducts an offset-point attack.
Key: (1) Take aim; (2) Initial point; (3) Automatic release point; (4)Bomb trajectory; (5) Target.

In the above three kinds of ground attack, the pilot requires the assistance of an inertia navigational system on all of them; e.g. guiding the aircraft to take aim at the target, flying over the target to memorize target or precision navigation from one point to another, etc.

In air-air dogfights, weapon systems require accurate real-time calculations of speed and angle(i.e. adopting the so-called "hot line" aiming device) in order to have the highest interception and attack efficiency. The inertia navigational system can provide signals such as true flight direction, pose angle, rate of change in pose and acceleration that are much more accurate than other equipment, and high accuracy of these signals can still be maintained during mobile flight; therefore, the attack power of a fighter can be most fully displayed when an inertia navigational system is incorporated with weapon systems.

Provide Sufficiently Accurate Navigational Position-Setting Information

For fighters, accurate position-setting is extremely important to both target capturing and pre-planning of flight cross-section. Whereas for long-range attack aircraft, first of all, it requires accurate navigation in order to reach the target, then comes the delivery of various weapons to attack the target and swiftly leaves before the enemy's defensive forces can effectively counterattack and selects the nearest destination or base for the return flight.

The inertia navigational system can provide sufficiently accurate position information for aircraft without the need for conducting in-flight adjustment, thus reducing the work load of pilot. The position-setting error of the inertia navigational system increases with time, and this is one of its weak points. However, the sustained flying time of combat aircraft is generally 2-2.5 hours and during this time the position-setting accuracy of the inertia navigational system is usually enough. But for long-range bombers, etc. which require very high navigation accuracy, then high-accuracy inertia navigational systems must be employed, or they must be supplemented with other navigational means.

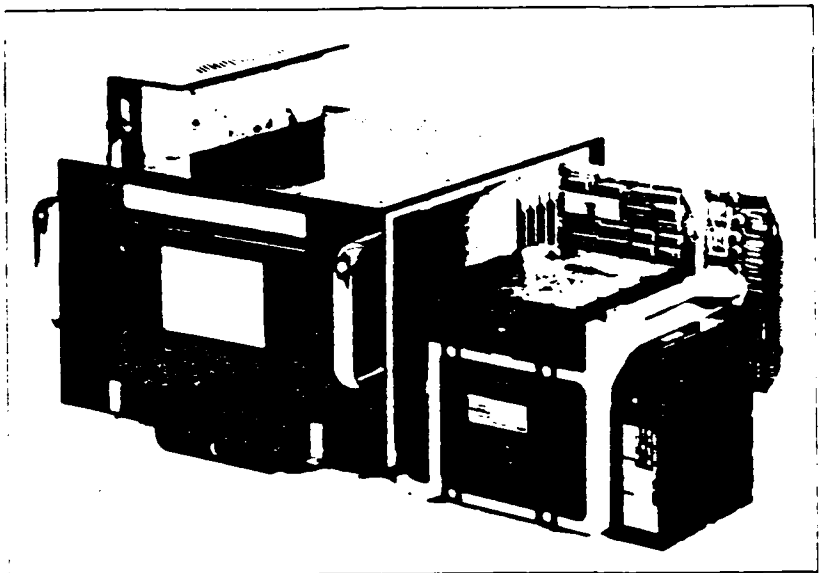
To summarize the above-described, the inertia naviagtional system is indeed an important electronic equipment for modern military aircraft. It not only is the primary navigational equipment on-board aircraft, but can also provide accurate pose standard for fire-power

control and flight control systems. Therefore, every single modern military aircraft is equipped with an inertia navigational system. There is such a contention that:"Electronics is changing the appearance of war; it makes war become automated.""Only with electronic technologies can it be possible to engage in dogfights, and today's air force must possess electronic systems which are technologically superior." It is exactly because of this that every country in the world with the capability to develop inertia technology is placing inertia navigation at an important position in its defense policy.

Quick-Connection Inertia Navigational System

In the past few years, aircraft inertia navigational systems employed have all been of a stable platform scheme, i.e.using a mechanical platform to separate inertia components from emergency reserve maneuver of aircraft. But this has been just an allowable, make-shift measure and the goal of engineering has been: with the removal of three(or four) framings---consequently the conduction ring, moment measurer and servo electronic devices that are attached to the framings are also removed, the reduction in weight, complexity and cost of the entire system is realized and the reliability is further increased; this is the quick-connection type inertia navigational system. The terminology "quick-connection", by its name, means to directly "tie" the inertia components onto the fuselage, and the effects of stable platform in the original framing system will be replaced by computer software functions in the quick-connection system. During the transition period from platform type toward quick-connection type, two technical obstacles must be overcome. One of them is that the computer and its associated software must be able to generate coordinates conversion from the aircraft to a certain stable coordinates system; the other one is that a gyroscope suitable for applications in the quick-connection system must be manufactured. With the amazing advances in computer technologies in recent years, especially the advances in resolving power and speed areas, the aforementioned first obstacle has been overcome first. With the successful manufacturing of a laser gyro in recent years, it has also provided an

ideal component for the quick-connection system. In fact, the quick-connection scheme is the largest developmental undertaking investment among inertia technologies in recent years; particularly, the laser gyro is the most important accomplishment of inertia technology in recent years, and its successful manufacturing has provided possibility for break-through in quick-connection technology, thereby opening up a new era of inertia technology.

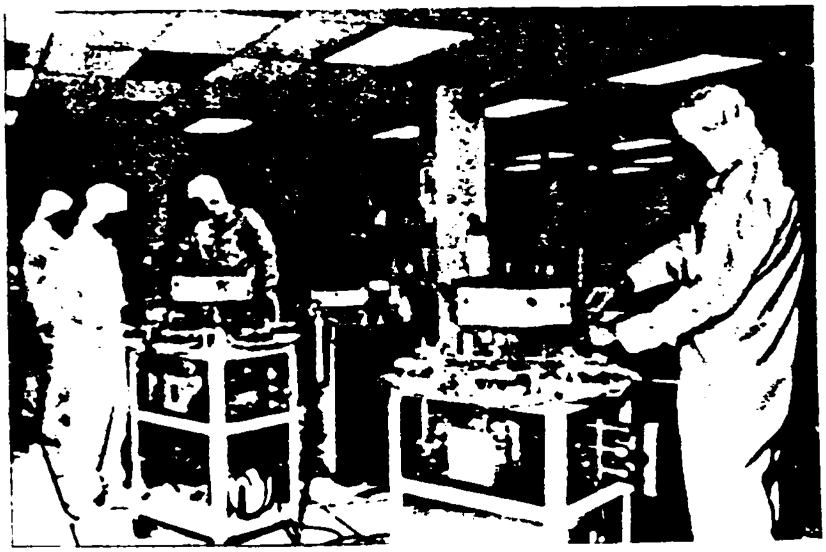


LTN-90 of Litton, Inc. is one of the more successful laser gyro inertia navigational systems, and there have been over 700 devices installed on A300, A310 Airbuses and the U.S. Navy E-6A airborne communications system.

Forecast of Market for the Quick-Connection System

The primary reason for navigational systems of military aircraft to change rapidly toward a quick-connection scheme does not lie in the area of navigation; it lies, however, in the requirements for a weapon delivery system. The gyroscope and accelerometer on board are all single-function. A modern fighter may need to use as many as 32 inertia components, and this is unacceptable in areas such as purchase cost, usage and maintenance and technical guarantee, etc. After adopting the

quick-connection system, the common inertia components can be used in flight control, navigation and weapon delivery, and it is estimated that the number of inertia components can be reduced to 12. This is one of the reasons for adopting the quick-connection scheme. More importantly, as far as obtaining pose and speed information of aircraft is concerned, the quick-connection type is much higher in both accuracy and completeness than the platform type, and this is an extremely important point for aiming systems of weapons.



Honeywell, Inc. of the U.S. currently takes up 90% of the market for an annular laser gyro. The figure shows a production line for the laser gyro of said company.

In 1978 the forecast on the applications of a quick-connection system by the U.S. Air Force showed that there would only be 10% of the market estimated for the quick-connection system with a harmonic rotor flexible gyro, whereas after adopting the laser gyro it could make the quick-connection inertia navigational system take up over 50% of the market. Since the laser gyro has obtained a successful breakthrough in recent years, now the more optimistic estimate is: by early nineties, the laser gyro will have taken up 70% of the gyro market. Currently, there is still an overlapping period of over 6 years between a laser gyro and a conventional

gyro. After the laser gyro enters mass production by 1990, the production type laser gyro inertia navigational system will become the standard issue product for the U.S. Air Force. Recently, the U.S. Air Force has determined that, within the domain of inertia navigational systems for military aircraft, the direction is to replace the conventional gyro with the laser gyro. For instance, an article which expounded the requirements for weapon delivery of an advanced tactical fighter for the nineties has pointed out that:"Laser gyro technology is the key point of an inertia navigational system for aircraft of the nineties." Another technical report published by the U.S. Pentagon in 1982 also stressed that:"The use of the laser gyro and an all-electronic system to replace a mechanical gyro can provide medium-accuracy navigation which adequately satisfies the demands of tactical missions."

Of course, in the meantime, the conventional gyro is still developing and it will continue to be produced until 2,000 to satisfy, on the one hand, the demands for parts and spares of aircraft inertia navigational systems currently in service and, more importantly, to develop toward a high degree of accuracy in order to satisfy certain special needs.

Laser Gyro and $F^3$ Standard Inertia Navigational Instrument

The gyroscope is the heart of an inertia navigational system. In order to guarantee that the position-setting accuracy of the inertia navigational system reaches 1 nautical mile/hour(this is the routine requirement for inertia navigational systems of combat aircraft), then it requires that the drift rate of the gyroscope does not exceed 0.01 degree/hour, i.e. reaching the so-called "inertia class". Before laser gyro, the gyroscope used in aircraft inertia navigational systems primarily includes types such as liquid-float, flexible, electrostatic, etc. For instance, during the entire seventies the flexible gyro platform inertia navigational system almost dominated the market of aircraft inertia navigational systems, and even today it is still being perfected and developed to become one of the primary implements on major combat aircraft of every country nowadays.

The laser gyro was invented by the U.S. in 1963. In 1973 it gained a significant technological breakthrough and the U.S. was the first country to use it on civilian aircraft in 1981. The reliability of annular laser gyro inertia standard system of civilian aircraft gives one a profound impression; hence, it finally makes the military believe that laser gyro is the direction for development. The feature that attracts the military's attention the most is that the average malfunction interval time of laser gyro inertia navigation for fighters exceeds 2,000 hours, whereas that for conventional inertia naviagtion is only several hundred hours.

The most important point is that the laser gyro fully satisfies the requirements of quick-connection system. Its major advantages are:

---It has no moving parts(meaning on its theoretical structure basis) and is a type of all solid-state device; therefore, it is sturdy, reliable, shock-resistant and has good anti-acceleration performance;

---It possesses an extremely wide dynamic range($>10^{-9}$) and is capable of avoiding cross-coupling errors caused by multi-axial sensitivity;

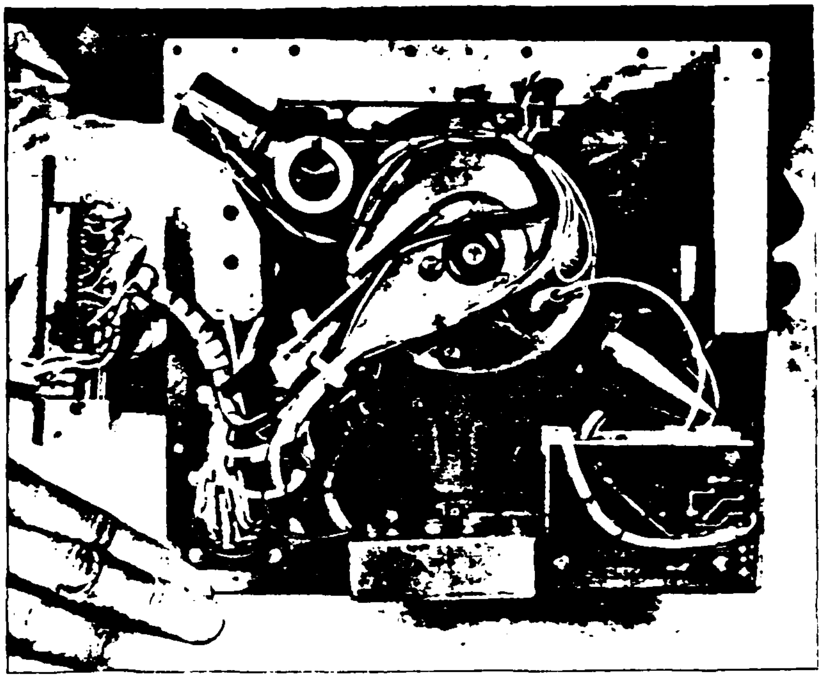
---Its startup time is short with preparation process almost being instantaneous;

---It employs direct digital input which is suitable for adopting the 1553B data main line with flexible applications;

---It possesses a prospect of low total cost. But the biggest problem faced today is still the inability of lowering production cost. At present, the cost of an inertia class laser gyro is about 8,000 U.S. dollars. It is expected that the cost can be lowered to 2,000-6,000 U.S. dollars with mass production.

During the developmental process of laser gyro technology, the U.S. has always maintained a dominant leading position. Just Honeywell, Inc. alone has provided 90% of the annular laser gyro systems for military and civilian markets, and its batch production capability of laser gyros has long reached 200 units/month. It has produced 2,200 annular laser gyros just in 1985 alone. In addition, Litton, Inc. and Singer-Kearfott, Inc. are also the major U.S. manufacturers of laser gyros. Litton's

batch production capacity of laser gyros has reached 250 units/month recently and Kearfott has also reached 100 units/month. The European laser gyro is on the verge of a breakthrough. The Dynamics Division of BAe, Inc. and Ferranti, Inc. of Great Britain are in the process of producing laser gyros for military inertia navigational system use. SFENA, Inc. and SAGEM, Inc. of France are also producing their respective laser gyro inertia navigational systems for fighters. Among these companies SFENA is probably in the leading position and already possesses the capability of producing in small batches of 15 units/month. The BAe, Inc also possesses the preliminary capability of producing 12 laser gyro units each month.



The laser gyro produced by the Dynamics Division of BAe, Inc. can be used on aircraft and guided weapons. Said company is previously known as Spelly Gyro Company. Its current monthly production capacity is 12 units.

The U.S. Air FOrce set forth standard bidding requirements for military laser gyro inertia navigational systems for the manufacturers of inertia navigational systems in November 1984 and this was a further development from the $F^3$ medium degree of accuracy standard inertia navigational instrument it had set forth in 1976. The proposing of a standard inertia navigational instrument was strictly for adapting to the new procurement policy of the U.S. military in order to counter the tremendous pressure on the national defense budget caused by the continuing increase in high procurement spending. The office of the U.S. Air Force Chief of Staff has decided that, when retrofitting old equipment, only standard electronic equipment is allowed to be adopted from now on. The so-called $F^3$ capability means the interchangeable capability in form, fit and function; in other words, the system is required to have standard fittings in four areas: mechanical, environmental, electrical software. The accuracy requirement for $F^3$ system is 0.8 nautical mile/hour, its standard marking time is 8-minute and its purchase expenditure is limited to within 60-80 thousand U.S. dollars/set(a set of flexible gyro platform inertia navigational systems is sold for about 150 thousand U.S. dollars). The navigational accuracy of the newly developed laser gyro standard inertia navigational instrument is still 0.8 nautical mile/hour, but the aiming accuracy for stored flight course after 90 seconds of heating has been changed from 3 nautical miles/hour to 0.8 nautical mile/hour. This is made possible due to the upgrading of accuracy for a stored flight course after employing the laser gyro.

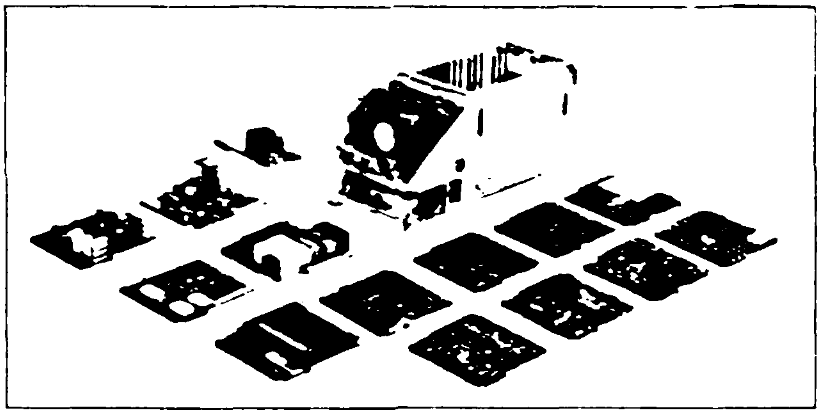
The $F^3$ system was first used on A-10 ground attack aircraft by the U.S. in early 1980, and subsequently it was used on F-16C/D model in 1983. The units equipped on these two types of aircraft were both the LN-39 model produced by Litton, Inc. and employed the platform system of a dynamicharmonic flexible gyro. The future new $F^3$ system project is:

---The inertia navigational system CAINS II of the next generation aircraft on-board carrier will adopt a laser gyro. Plans are to use it on the remodelled F-14D and A-6E and the competition is between Kearfott and Litton. The production contract is expected to be finalized in early

1987;

---Based on the laser gyro inertia navigational system already installed on F-20 and JAS39 fighters, $F^3$ standard inertia navigational instruments will be selected for F-15, F-111, RF-4C, C-130 and HH-60. The U.S. Air Force plans to purchase 5,000 sets and the competition is being waged between two companies, Honeywell and Litton. The first cut-over will be in 1987;

---The laser gyro inertia navigational systems for military aircraft currently being manufactured by France and Great Britain also comply with the $F^3$ standards. The British target is to employ it on the modified "Tornado" and the West German remodelled F-4F, and the time is set for late eighties to early nineties; the French target is the experimental fighter ACX currently being built and plans are to produce a prototype in 1986 for test flight.



The first kind of $F^3$ standard military inertia navigational instrument LN-39 of the U.S. Air Force has been installed on A-10 and F-16C/D fighters.

It needs to be emphasized and pointed out here that it is quite popular among countries to retrofit old aircraft with inertia navigational systems in recent years. On the one hand, countries such as the U.S., Great Britain, France, etc. which possess true capability in inertia navigational technology are in the process of completing the transition from platform type to quick-connection type inertia naviga-

tional systems for military combat aircraft; in the meantime, the retrofitting of flexible gyro platform systems on frontline aircraft for certain countries is also in progress, among which are F-4EJ of Japan, J35 of Denmark, "Phantom" of Pakistan, "Cougar" of India, F-4 of South Korea, Australia and Malaysia, etc.

## Combined Navigation Based on Inertia

In view of the current developmental level of the inertia technology, the accuracy of pure inertia system is already capable of satisfying demands of the present various tactical weapon systems, and even within several years from now it will still maintain a specific accuracy potential. However, as new technologies such as Carman filtered wave, satellite navigation, etc. become mature, the combined navigational system based on inertia can make different navigational means supplement one another. Especially, while conducting long distance navigation or certain missiles which require special,high-accuracy navigation, a pure inertia system frequently can not satisfy demands. Therefore, a combined navigational scheme has constantly obtained research and applications.

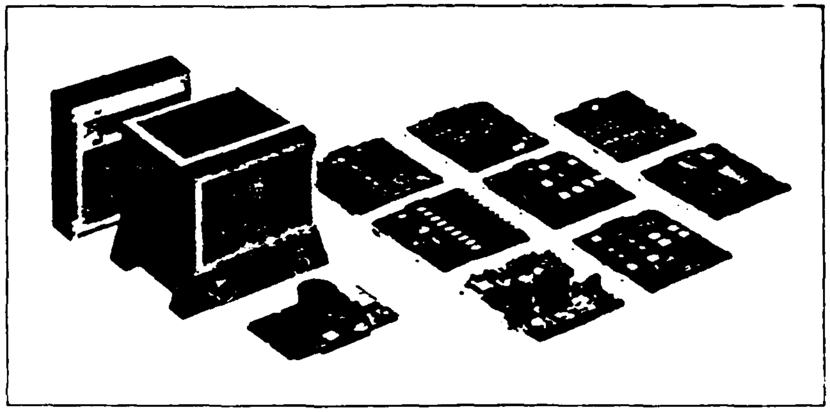
## Inertia-Doppler Combined System

Both inertia navigation and Doppler navigation are independent type navigation. In the combined system of the two, an inertia system will display the merits of excellent, short-time, dynamic response, whereas the independent measurement data provided by the Doppler system can damp the 84-minute shock of inertia navigation and limit divergence of errors. Utilization of such a system allows adoption of a gyro with not so high accuracy(e.g. drift rate is 1 degree/hour), thereby reducing cost of the entire system. This is one of the features of this kind of combined system.

In military helicopters, the Doppler system is an indispensible equipment used for measuring small ground speed while hovering. Therefore, there are more applications of an inertia-Doppler combined system in

helicopters. In addition, there are also large aircraft which use this as a spare navigational device(such as the C-130 remodel project planned to be completed in 1990). Typical applications of inertia Doppler combined navigation are:

---The LR-80 quick-connection type flight course pose/Doppler combined system used by the U.S. AH-64 armed helicopter has the highest performance among similar products. It is the product of Litton, Inc. of the U.S.;

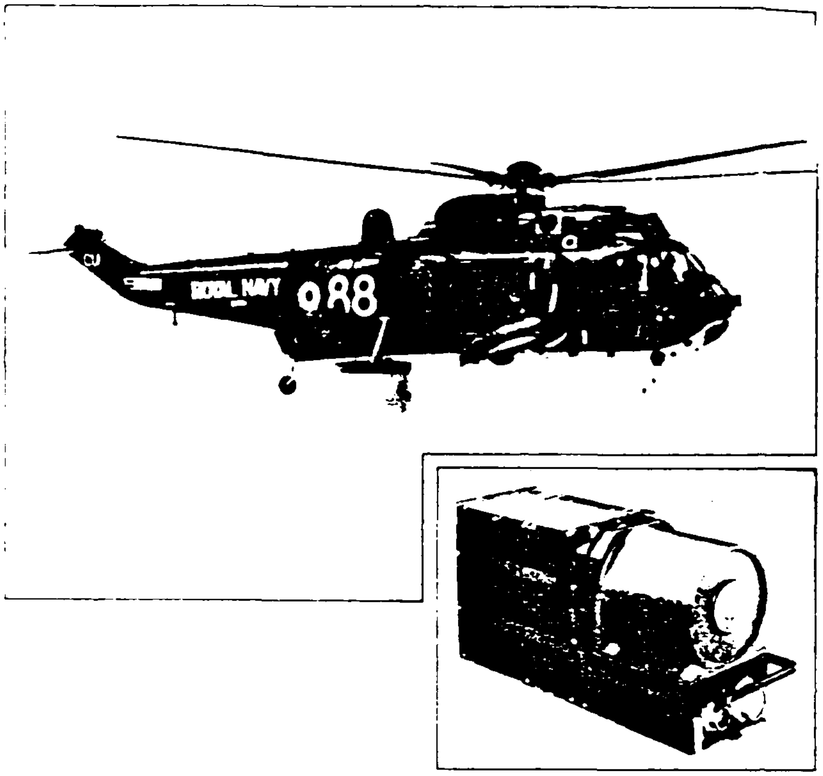


The LR-80 quick-connection type inertia/Doppler combined system equipped on the U.S. AH-64 "Apache" helicopter.

---The "Poseidon" early warning helicopter of the British Royal Navy uses the FIN1110 double framing inertia navigational system. The drift of said system itself is about 5 nautical miles/hour, but after combining with Doppler speed input the drift is reduced to 1 nautical mile/hour and the price after combining is only 50-60% of that of a pure inertia navigational system with equivalent performance. Said system is the product of Floundy, Inc. of Great Britain;

---Test flights have shown that the 28SH quick-connection type flight pose system planned to be used on PAH2 armed helicopters has a navigation error of 0.47% of distance flown after combining with Doppler

system, and its price is only half of that of an inertia navigational system with the same performance. Said system is the product of SFIM, Inc. of France.




The "Poseidon" early warning helicopter of the British Navy. The inset shows the FIN1110 double framing inertia navigational system installed on said aircraft.

Celestial-Inertia Combined System

In long-range bombers, there is a combination scheme of a celestial-inertia combined system, i.e., through opti-electrical star tracker to calibrate and adjust inertia platform in order to reach the goal of upgrading accuracy of the entire system.

The celestial inertia system NAS-26 manufactured by Northrop, Inc. of the U.S. will be installed on B-1B long-range strategic bomber as the spare of SKN-2440 high-accuracy inertia navigational system

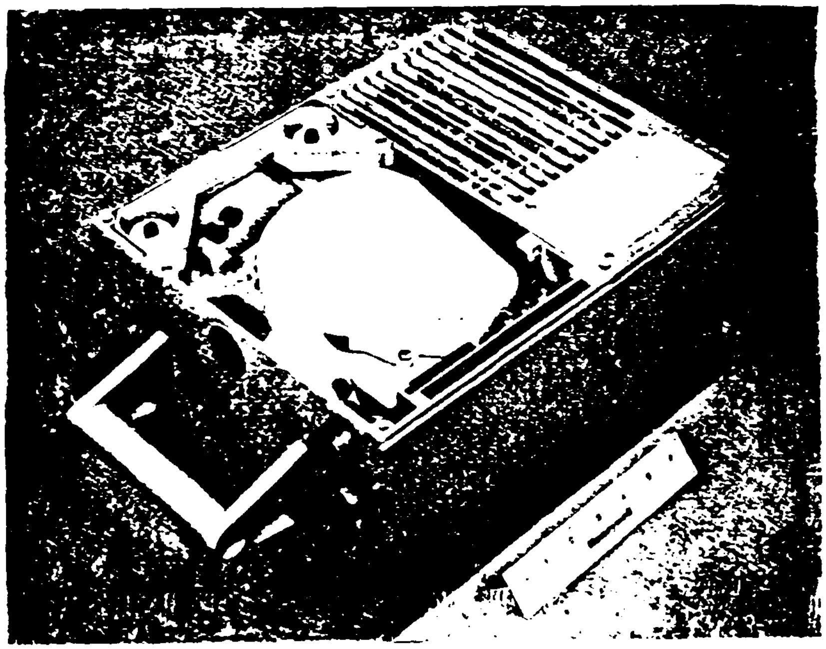
provided by Kearfott, Inc. The NAS-26 system can reduce positional probability error down to far lower than the level of 305 meters and is independent of time.

Inertia-Satellite Navigation Combined System

The American Navstar satellite navigational global positioning system (GPS) uses the technology of conducting navigation through a man-made satellite. In theory, it is not much different from the ordinary radio navigational system except that the navigation tower on the ground is moved onto a satellite which moves according to specific rules, and meanwhile an additional set of ground facility is installed to observe and forecast satellite positions. Combined GPS and inertia navigation, through Carman filtered wave, can give much higher accuracy than the single system; for example, positioning accuracy of 40 meters can be obtained using the commercial C/A code as opposed to the positioning accuracy of 16 meters obtained using the military P code.

F-14 armed with 6 "Phoenix" long-range air-to-air guided missiles. The U.S. Navy is in the process of manufacturing the CAINS II, which is the second-generation standard carrier-based aircraft inertia navigational system and employs a laser gyroscope, for a new generation of F14D. In addition, the navigational equipment is possibly the combination of quick-connection inertia navigation/satellite navigation.

Presently, only incomplete GPS coverage is provided worldwide since navigational satellites have not all been launched. The 24-hour global operation will be realized by 1988 when all 18 "Navstar" satellites will have been launched. For this reason, the U.S. announced a new radio navigational plan in 1984. The new plan calls for migration to navigational satellite global position-setting systems by military users beginning in 1988 and progressive elimination of "Lowlan" C/D, "Omega", "Tycoon" and VOR/DME adopted by the military sector. If the performance of a navigational satellite can satisfy required conditions, it will even become the equipment for commercial users and replace "Lowlan" C and "Omega". This new project has already been approved by the U.S. Defense Department and Transportation Department.



The annular laser gyro inertia navigational system H421 installed on the U.S. Navy fighter AV-8B.

Currently, countries such as the U.S., Great Britain, France, etc. are in the process of research and manufacturing a satellite navigation-inertia navigation combined scheme. The advanced inertia system using a dynamic harmonic gyro, which is manufactured by Northrop, Inc. of the U.S. will be designated as standard flight pose system for the military services in 1987. When update of the "Navstar" global position-setting system is available, the gyro accuracy is 0.01 degree/hour, as opposed to 0.1 degree/hour without update, and the batch production price is established at 50-60 thousand U.S. dollars. The research and manufacturing undertakings of the said company also indicate that if a 5-channel receiver of the "Navstar" global position-setting system is combined with a high-performance inertia navigational system, the price could reach 150-180 thousand U.S. dollars. In addition, test flights scheduled for the F-14D modification project in 1989 will employ a combination of laser gyro quick-connection system and the "Navstar" global position-setting system technologies. The Saigus, Inc. of France is also considering to include the "Navstar" global position-setting system in its bidding for the A320 passenger aircraft navigational system. Said system is called atmospheric data inertia datum system(ADIRS) and the inertia portion will employ a laser gyro.

## Conclusions

As far as the new military aircraft manufactured by various countries from the eighties to the nineties, they will all be equipped with improved or new-generation inertia navigational systems without a single exception. It can be predicted that the development of aircraft inertia navigational systems is just unfolding and the speed of technological improvement will not be reduced. The future market will be crowded and the competition will also be fierce.

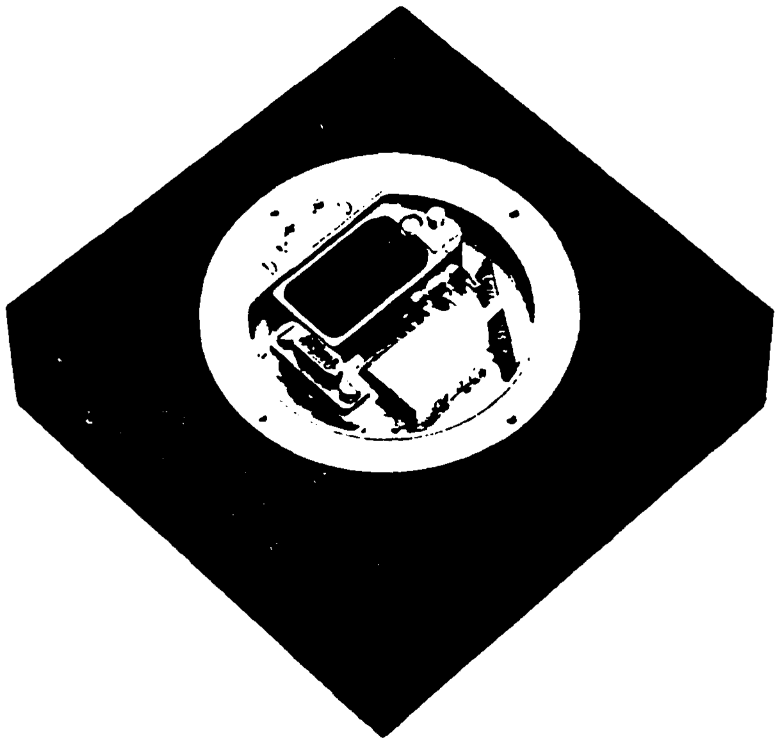
FIBEROPTICAL GYRO---THE NAVIGATIONAL INSTRUMENT OF THE FUTURE

Huang Shanhu

By estimation, a fiberoptical gyro can only gain application in military equipment in the late eighties; however, it is superior to an annular laser gyro in areas such as size, reliability, cost and integrated optical circuit technology, etc. Today, the annular laser gyro is progressively replacing conventional electromechanical gyros; tomorrow, the annular laser gyro will be replaced by the fiberoptical gyro.

A gyroscope is one of the key components of inertia navigation. A conventional gyroscope (i.e., electromechanical gyroscope) uses the directional and mobile properties of a high-speed rotating mechanical rotor to measure the rotational speed and direction relative to the inertia space. After the advent of the laser in 1960, countries such as the U.S., Great Britain, France, Soviet Union, etc. almost began research of laser gyros simultaneously in 1962. The principle of the laser gyro is different from that of the electromechanical gyro in that it does not have moving parts; rather, it relies upon laser beam transmission to accomplish its functions. Therefore, it possesses many unique advantages and has received much attention from various countries. The U.S. had successfully tested a laser gyro on tactical aircraft and tactical guided missiles, respectively in 1975 and 1976,

thereby displaying an extremely broad prospect. At the same time with this, people had devoted more enthusiasm in applying fiberoptical technology to a laser gyro where optical fiber is replaced by an annular harmonic cavity and a reflective mirror, thereby starting the research in fiberoptical gyros in the hope of developing more new and practical devices.



Fiberoptical gyroscope manufactured by SEL, Inc. of West Germany.

Principle and Characteristics of Fiberoptical Gyros

The operating principle of fiberoptical gyros is built upon the basis of Saganauk interferometer effect and the operation process is as shown in Fig. 1: a laser beam is divided in half using a spectroscope; the first half is fed into one end of the fiberoptical coil, and the other half is fed from the other end of the coil, transmitting along a counterclockwise direction; after these two laser beams transmitting along the opposite directions in the fiberoptical coil

emit from both ends, they are again combined by the spectroscope and the combined beam will produce a bull's-eye ring with an alternating bright and dark interference pattern. If the fiberoptical coil is stationary, then the two beams should possess the same phase because they transmit an identical distance through the same medium. When the coil rotates around the axis the phases of the two light beams emitting from both ends will change. The magnitude of phase shift is directly proportional to the angular velocity of the coil, and the direction of phase shift indicates the rotational direction. figure 2 shows the structure of a fiberoptical gyro.

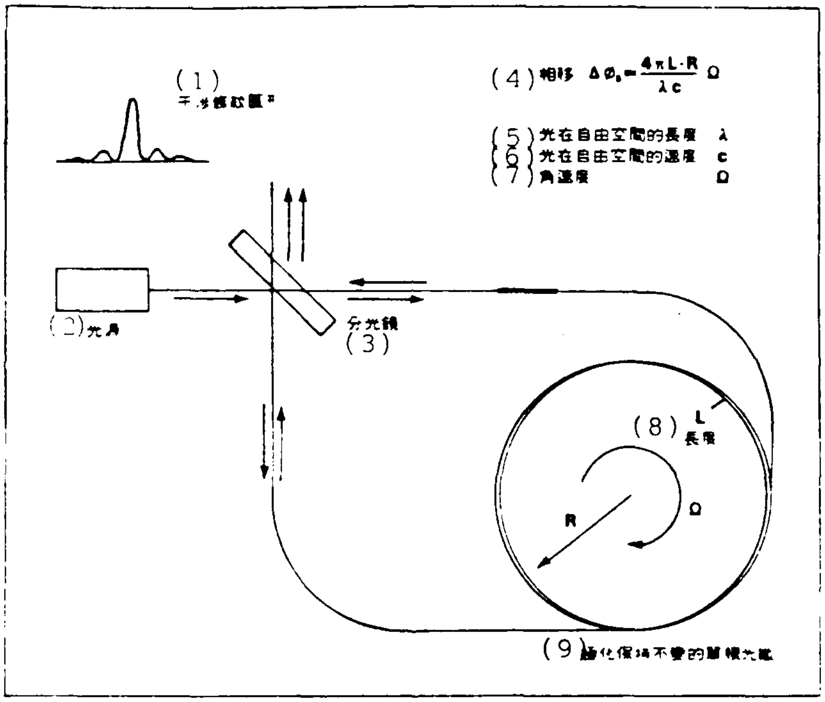



Fig. 1. Operational process of fiberoptical gyro
Key: (1) Diagram of interference pattern; (2) Light source; (3) Spectroscope; (4) Phase shift; (5) Length of light in free space; (6) Speed of light in free space; (7) Angular velocity; (8) Length; (9) Single-mode optical fiber with constant polarization.

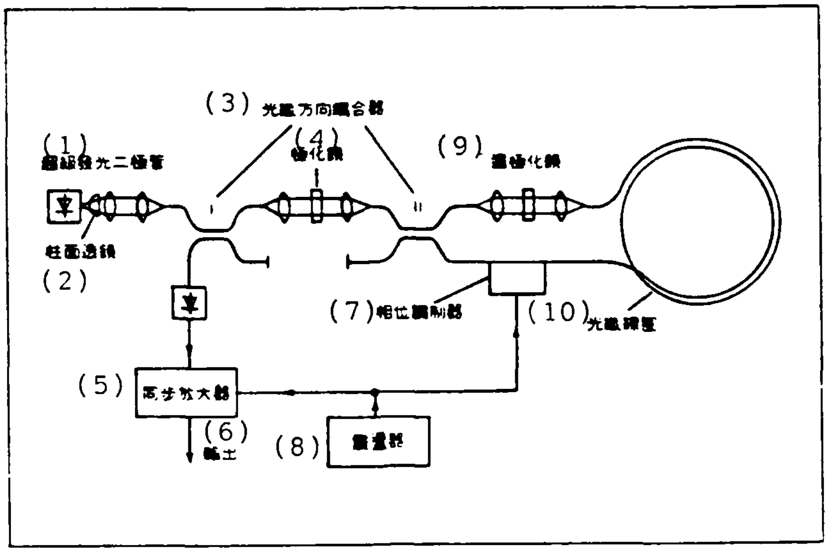



Fig. 2 Structure of fiberoptical gyro
Key: (1) Super light emitting diode; (2) Prism; (3) Fiberoptical direction coupler; (4) Polarization mirror; (5) Synchronous amplifier; (6) Output; (7) Phase adjustor; (8) Oscillator; (9) Depolarization mirror; (10) Fiberoptical coil.

The fiberoptical gyro not only possesses the strong points of a laser gyro---e.g. insensitive to gravitational acceleration and its square effect and overlapping effects, large dynamic range, high reliability, simple structure, low cost, but also has its own unique advantages:

(1) High potential sensitivity and accuracy. The sensitivity of the laser gyro is determined by the size of enclosing area of the reversely rotating laser beam; yet besides increasing with the increase in coil area, sensitivity and accuracy of certain fiberoptical gyro also increase as the number of rounds of optical fiber in the coil increases.

(2) Resolving the problem of so-called "model lock". The optical circuit of the laser gyro's reversely rotating light beam is also the laser harmonic cavity body, thereby causing additional interaction between the reversely rotating light beams and the so-called "model lock" problem, and making the laser gyro insensitive to the response of very small

angular velocity. The fiberoptical gyro, however, does not have this problem because it uses external light source (e.g., light-emitting diode) and adopts optical fiber as the only transmission medium. According to current technological level, the dynamic measuring ranges are: speed of rotation is 0.00008-1,000 degree/sec; angular velocity is 1,000 degree/sec$^2$.

(3) Smaller in dimensions. The miniaturization of the laser gyro must pay the price of reduction in sensitivity and accuracy, whereas for a fiberoptical gyro this is not the case because the diameter of optical fiber is only several dozen to several microns and can be wound into a miniature sensitive coil with a great number of rounds. For instance, the low cost gyro of which Great Britain plans to begin production in the nineties has a diameter of only 75 milimeters, a thickness of 12 milimeters and weight of 75 grams.

(4) Lower cost. It is possible for fiberoptical gyros to employ microelectronics manufacturing technology, realize semi-qutomatic mass production and reach the goal of reducing cost. By estimation, the manufacturing cost of fiberoptical gyro is 50 times lower than that of the typical annular laser gyro. The selling price of a simple fiber-optical gyro device is only 1,000-1,700 U.S. dollars.

(5) Early to adopt integrated optical circuit technology. Experts have analyzed that future fiberoptical gyros will use integrated optical circuit components to replace individual components of the current experimental fiberoptical gyro so as to further reduce dimensions, weight and cost, simplify assembling technology as well as upgrade its durability and reliability in order for it to be able to adapt to the needs of high impact and strong shock environment.

## Primary Technical Problem and the Approach to Solutions

### "Second Light Refraction" Problem

A fiberoptical gyro usually employs single-mode optical fibers to wind into sensitive coils. When a light beam passes through a coil, it generally can not maintain its initial polarization form and will be linearly polarized, that is, alternatingly producing horizontal and vertical polarization, and this phenomenon is called the "second light refraction". Since the propagation speeds of concurrent and countercurrent polarization waves are slightly different, this so-called polarization pollution will generate a kind of uncertainty in the phase comparison measurements, i.e. "noise". As far as the application of a fiberoptical gyro is concerned, polarization drift is a serious problem because in order to improve polarization stability by 20 decibels the accuracy and sensitivity of the sensor must be upgraded by 10 times. In addition, when external light source couples with single-mode optical fiber(with inner diameter only a few microns), part of the light is also reflected back to the laser device, causing the spectrum purity of laser device to degenerate thereby producing additional noise in the sensor. Presently, various technical approaches have been employed to resolve the polarization stability problem of single-mode optical fiber such that extremely low "second light refraction" is resulted.

One of the solution methods is to use an elliptical optical fiber wick to replace the circular optical fiber wick in order to upgrade polarization stability. Allegedly, Andrew, Inc. can provide elliptical optical fiber samples. The dimensions of the elliptical wick is 1x2.5 micron, but the loss of optical fiber is greater, about 40 decibels/kilometer. The magnitude of loss is, to a very large extent, determined by wiredrawing stress during the manufacturing process, and by further improving wiredrawing technology, it is possible to reduce the loss of optical fibers.

Another kind of solution method is to impart a deform-controlling stress(prestress) to the wrapping materials of a circular fiberoptical wick in order to improve polarization stability. According to disclosure, Hitachi, Inc. of Japan has obtained significant progress in this research area of polarization stability for optical fibers.

Still another kind of solution method is to adopt the multi-strain optical fiber twisting technique to alleviate the "second light refraction" problem. Currently, a kind of equipment which suits the manufacturing of 28-strain twisted optical fibers is already available.

## Effects of Temperature, Magnetic Field, Unbalanced Internal Heating of Optical Fibers

Except for the polarization stability of elliptical wick which is not affected by surrounding temperature, the aforementioned so-called adoption of prestress and twisting technique for optical fibers are all affected by temperature. Furthermore, magnetic field will also affect polarization, which implies that the protective screen and compensation of magnetic field must be performed for a fiberoptical gyro. Moreover, unless the laser output can be discreetly separated into two, the concurrent and countercurrent light beams fed into the two ends of optical fibers will also generate unbalanced heating effects in the interior of optical fibers thereby causing serious problems, for if the fiberoptical wick diameter is assumed to be 3 microns and laser input is only 1 miliwatt, then the power density of the optical fiber will reach as high as 10 kilowatts/$cm^2$.

## General Status of Development and Prospect of Applications

The U.S. began demonstrative research of a fiberoptical gyro in 1976. Massachusetts Institute of Technology of the U.S. held a fiberoptical gyro convention at the end of 1981 and 150-odd gyroscope manufacturers from the U.S. and Europe participated. Unexpectedly, the majority of companies and laboratories which lead in fiberoptical gyro technology(e. g. Martin-Marietta/Olin, Inc., McDonald- Douglas, Inc. of the U.S., AEG-Delufangen, Inc. of West Germany and Thomas Radio, Inc. of France,etc.) are not necessarily the manufacturers that engage in the manufacturing of conventional gyroscopes. Of course, some of the suppliers of conventional gyroscopes(e.g. Honeywell, Inc., Rockwell International, Inc. of the U.S., Terdix, Inc. of West Germany) are also studying this new

technology. In addition, many universities such as Massachusetts Institute of Technology and Stanford University of the U.S., Sausanpton University of Great Britain, Hamburg University of West Germany, Pavia University of Italy and Tokyo University of Japan are also engaging in the research of this area. The U.S., due to the investment by the Army, Navy, Air Force and NASA, has made her development in fiberoptical gyros situated in a leading position.

Performance comparison of fiberoptical gyro prototypes

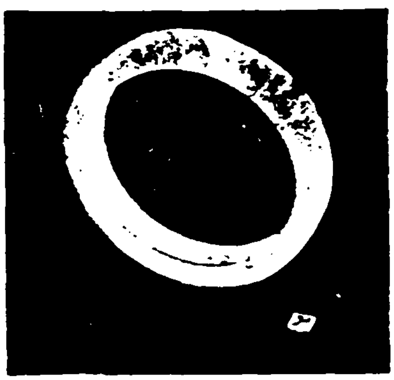
| (1) [illegible] | (8) [illegible] | (9) [illegible] | (15) [illegible] | (16) [illegible] | (17) [illegible] | (24) [illegible] |
|---|---|---|---|---|---|---|
| [illegible] (2) | 0.2 | (10) GaAs [illegible] $\lambda=0.83\mu m$ | 580 | 14 | (18) [illegible] | (25) [illegible] |
| [illegible] (3) | 0.02 | (11) [illegible] 三模式 He Ne [illegible] ($\lambda=0.63\mu m$) | 200 | 19 | (19) [illegible] | (26) 分立元件 |
| [illegible] (4) | 0.7 | — | 1,200 | 30 | (20) [illegible] | (26) 分立元件 |
| [illegible] (5) | 1.6 | (12) He Ne [illegible] ($\lambda=0.63\mu m$) | 150 | — | (21) [illegible] | (26) 分立元件 |
| [illegible] (6) | 10 | (13) [illegible] $\lambda=0.82\mu m$ | 800 | 20 | (22) [illegible] | (26) 分立元件 |
| [illegible] (7) | 100 | (14) GaAs [illegible] ($\lambda=0.83\mu m$) | 88 | 12 | (23) [illegible] | (26) 分立元件 |

Key: (1) Manufacturing company; (2) Stanford University; (3) Massachusetts Institute of Technology; (4) Martin-Marietta, Inc.; (5) Honeywell, Inc.; (6) Delufangen, Inc.; (7) McDonald-Douglas, Inc.; (8) Drift rate; (9) Light Source; (10) GaAs semiconductor laser device; (11) Triple-mode He-Ne gaseous laser device with frequency scanning; (12) He-Ne gaseous laser device; (13) Super light-emitting diode; (14) GaAs semiconductor laser device; (15) Length of optical fiber(m); (16) Diameter of coil(cm); (17) Features of testing electrical circuit; (18) Testing electrical circuit with phase adjustment; (19) With phase compensation, second-order harmonic wave approaches zero; (20) With phase compensation, first-order harmonic wave approaches zero; (21) Application double polarization; (22) With phase adjustment; (23) With phase compensation, first-order harmonic wave approaches zero; (24) Structural characteristics; (25) All optical fibers used; (26) Separate components.

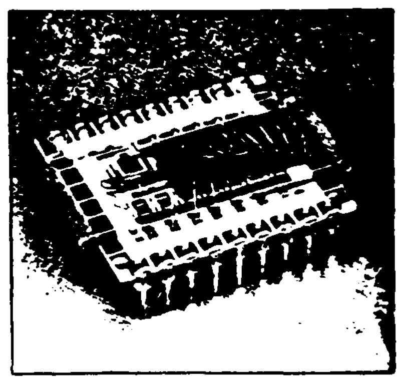
The drift rate of a current typical laser gyro is better than 0.01 degree/hour; this means that it is capable of reaching an accuracy of an error of 1 nautical mile for every hour of flight for aircraft's inertia navigational system. In view of the performance of several current fiberoptical gyro prototypes(above Table), however, the drift rate of only a few prototypes reaches 0.7~0.02 degrees/hour and many prototypes still lag rather far behind laser gyros. Someone has estimated the sensitivity of a fiberoptical gyro from dispersion noise of probe and found it to reach

$2.4 \times 10^{-3}$ degree/hour. This not only shows that there still exist a number of error factors that are much greater than dispersion noise (for example, the nonperfectness of single-mode optical fiber) which awaits further solution and it also indicates that there is still great potential to be tapped in upgrading the sensitivity of a fiber-optical gyro. A number of uninversities and companies are actively engaging in this research undertaking.

The experimental fiberoptical gyro manufactured by McDonald-Douglas Aerospace, Inc. using zero-phase method can provide digital output and its accuracy is not determined by the fiberoptical coil; rather, the sensitivity is upgraded with increase in the length of optical fiber. Said company is also manufacturing fiberoptical gyros with drift rate of 0.1-10 degrees/hour and is developing the technology and components which will eventually make the drift rate of fiber-optical gyros reach 0.01 degree/hour.



Fiberoptical coil



Integrated optical circuit

Stanford University has proposed a new kind of design method called "pulse closed annulus". This is different from ordinary design in that the two ends of the sensitivity coil of this device is connected together to allow for self-closure of optical circuit; therefore, a light beam can transmit several times along the annular path thereby achieving the goal of upgrading sensitivity. However, a light amplifier must be linked up at the connection end of the optical fiber to make up for losses of fiberoptical transmission and and allow a light pulse to regenerate. The Saganawk phase between pulses will change linearly with time. Sampling and combining of these pulses are conducted, and through appropriate wave filtration,

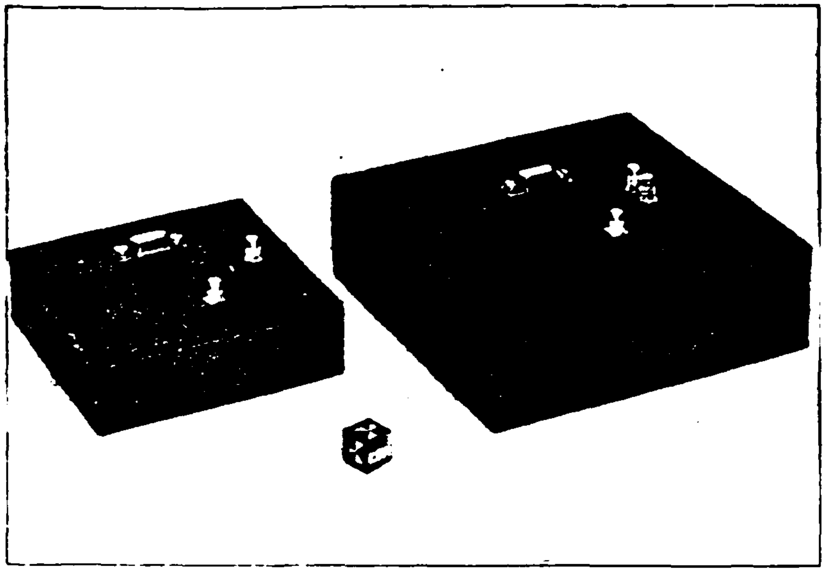
a modulated sine pulse chain can be obtained with its contour containing rotational information. If a wave is filtered again, then only the contour of the pulse chain remains and the frequency of this kind of sine contour will be proportional to the rotational speed of the sensor thereby realizing digital output. This kind of experimental fiberoptical gyro has been successfully manufactured at Stanford University and is very easy to adjust and use.

Honeywell, Inc. has produced a kind of experimental device called dual-polarization fiberoptical gyro, and its light source He-Ne laser beam is of 45-degree polarized wave. This is equivalent to feeding a horizontally and vertically polarized wave into the two ends of a fiberoptical sensitive coil. Compared with the design of more common, zero-difference type fiberoptical gyro, the performance of this kind of fiberoptical gyro can be upgraded by about one order of magnitude and the size reduced in half, and is least affected by the changes in temperature. It uses optical fibers 150 meters in length with a long-term drift rate about 50 degrees/hour and short-term drift rate 1.6 degrees/hour.

The Alsogondo Aerospace, Inc. in California of the U.S. utilizes a linear matrix composed of 1,728 electric charge coupling device (CCD) to measure the output of laser gyro at the rate of 16 times every second. After the measured signals are amplified, filtered and converted by a 12-bit digital converter, analysis is conducted using micro-computer and it is anticipated that the interference pattern location can be measured to $10^{-5}$ stripes, upgrading the measurement accuracy 100 times over the general method and bringing hope to pragmatization of fiberoptical gyros.

A fiberoptical gyro possesses very broad application potentials. Experts have analyzed that a medium-performance fiberoptical gyro with drift rate of 10 degrees/hour is sufficient to satisfy navigation of tactical guided missiles, vehicles and small ships as well as the needs of industrial control and robotic control; whereas a high-performance fiberoptical gyro with drift rate of 0.01 degree/hour can satisfy the utilization needs of aircraft, long-range strategic guided missiles,

space flight vehicles and large ships. By estimation, it will be the late eighties before fiberoptical gyros can be provided for the use of combat systems. ITT, Inc. predicts that during the 10 years from now it is possible to open up a new market for 100 thousand fiberoptical gyro devices.



Speed gyro and speed integrated gyro

To summarize the aforementioned, since a fiberoptical gyro possesses features such as light weight, high reliability, inexpensive price, easy to combine with integrated optical circuit technology, etc., thus it forms a strong potential prepoderance. If it is said that in the near future laser gyros with light source cavity and using reflection mirror will replace the majority of conventional electro-mechanical gyros, then, after a relatively long period of time, it is also the certain developmental trend for fiberoptical gyros to replace laser gyros with a light source cavity.

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